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The Argon Dark Matter Experiment (ArDM)

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Abstract.
The ArDM experiment, a 1 ton liquid argon TPC/Calorimeter, is designed for the detection of dark matter particles which can scatter off the spinless argon nucleus, producing nuclear recoils. These events will be discerned by their light to charge ratio, as well as the time structure of the scintillation light. The experiment is presently under construction and commissioning on surface at CERN. Cryogenic operation and light detection performance was recently confirmed in a test run of the full 1 ton liquid argon target under purely calorimetric operation and with a prototype light readout system. This note describes the experimental concept, the main detector components and presents some first results.

1. Introduction

The best limit on spin-independent WIMP cross-sections is presently given by the CDMS experiment [1], which records phonon and ionisation signals of particle interactions in cryogenic semiconductor targets [1] with high sophistication. A row of noble liquid dark matter experiments are currently striving for a similar kind of experimental perfection, actually starting to challenge these best limits [2]. While noble liquids are equally blessed with high scintillation and ionisation yields, they feature a high potential to be scaled up in the ton or even multi-ton target range, which makes this technology so popular and rapidly progressing. Large target sizes require very high radiopurity of the target, not only to limit feedthrough of background in the nuclear recoil band, but also to comply with a maximal tolerable trigger rate. This is a main concern in the case for liquid argon (LAr) due to the long lived ^{39}Ar isotope. Recent progress in liquifying underground gases and extracting substantial quantities of ^{39}Ar depleted liquid argon gives however a promising outlook for this technology. Self-shielding [2], one of the strongest motivations to go to large masses, is very much improving for larger and larger target sizes. Further on a large detector is able to determine, on a statistical base, the background of single scattering neutrons in the data from the multiplicity distribution of neutron interactions. Figure 1 shows

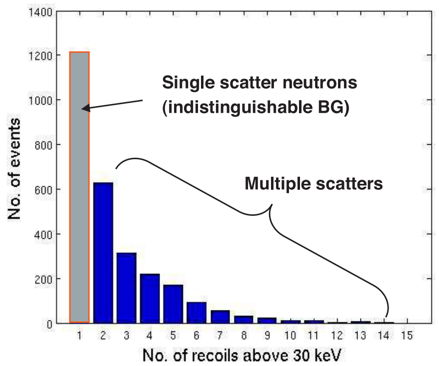

Figure 1. Interaction multiplicity of background neutrons in ArDM (MC).

[1] Total target mass is around 6 kg
[2] against external radiation, above all gammas, but not neutrons

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a frequency distribution of neutron interactions on the example of the ArDM geometry [3]. A hydrogen rich shield will nevertheless be used to protect the detector in its final working location from background neutrons (after a measurement of the spectrum).

In liquid argon, both, the scintillation light to charge ratio and the temporal structure of the light emission [4, 5, 6] can be used for electron- to nuclear-recoil discrimination. This is due to the ionisation density dependent ratio of the two argon excimer ground states ($^1\Sigma_u^+$ and $^3\Sigma_u^+$), which are responsible for the VUV luminescense of LAr. The large difference of their radiative lifetimes ($\approx 10^3$) allows for excellent recoil separation down to 20 keV_{ee} (electron equivalent scale) [7]. This effect alone is used to classify recoils by some single phase experiments (e.g. DEAP/CLEAN, XMASS [8, 9]). The two phase configuration (as we employ it in ArDM) allows for an additional measurement of the ionisation charge (e.g. XENON, WARP, LUX [10, 11, 12] experiments). A drawback of the argon technology is the short wavelength of the scintillation light (128 nm) and the already mentioned presence of the ^{39}Ar β-emitter. However, because of form factors, argon is less sensitive to the threshold of the nuclear recoil energy, than is e.g. xenon. For the same reason the recoil energy spectra of argon and xenon are quite different. These liquids are therefore complementary in providing a crosscheck once a WIMP signal has been found.

2. Conceptual design

ArDM [13] was projected as a ton scale liquid argon spectrometer aiming at the detection of nuclear recoils above 30 keV_r (i.e. $\approx$ 10 keV_{ee}). At the same time it serves as a prototype unit for future large LAr detectors, for more sensitive DM experiments or next generation neutrino observatories. Three dimensional imaging and event by event interaction type identification will be used to reach high background suppression. About 400 VUV photons and a couple of ionisation charges[3] are typically produced in LAr by a WIMP interaction at 30 keV. The background rejection will be achieved by the combination of cuts on the fiducial volume, the event topology (excl. multiple scatter), the light to charge ratio and the temporal structure of the light emission. The technical requirements comprise a large volume electric field, a large area position sensitive charge readout (3rd dimension from drift time), a fast and large area light readout and an efficient liquid argon purification system. The event trigger is generated from the light signal. Figure 2 shows a sketch of the two-phase operating mode of the detector. In a particle interaction excited and ionised argon atoms form the argon excimer states [5] which decay under the emission of 128 nm VUV radiation. This light can not be absorbed by neutral argon atoms and hence propagates to the side walls of the detector which are coated with the wave shifting material tetraphenyl-butadiene (TPB). VUV light is absorbed and with high efficiency re-emitted at around 430 nm, the region of high quantum efficiency of borosilicate windowed bialkali PMTs. By diffusive reflection on the side walls, the light is transported to the bottom of the apparatus to an array of 14 hemispherical 8" PMTs. The strong electric field is capable of preventing some free electrons in the densely ionised region around a nuclear recoil from recombining and sweeps them to the surface of the liquid, where they are extracted into the gaseous phase of the detector. The

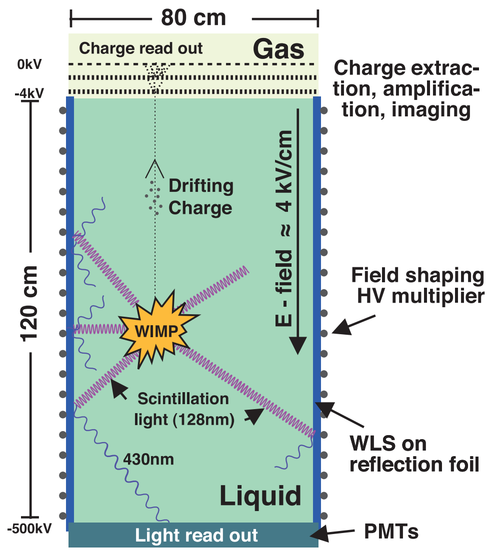

Figure 2. Conceptual design of ArDM.

[3] if the electrical field is above 1 kV/cm

charges are then multiplied by means of a rigid large gas electron multiplier (LEM) and finally recorded by a position sensitive read out plane [14].

3. The experimental components

Figure 3 left shows the mechanical arrangement of the cryogenic cooling and cleaning system of the setup together with the main stainless steel dewar (containing roughly 1800 kg of liquid argon). An inner cylindrical volume of 80 cm diameter and 120 cm height is delimited by round ring electrodes (field shapers) constituting the 850 kg active LAr target in a vertical TPC configuration (Fig. 3 middle). The field shaper rings are connected to a 210 stage HV diode-capacitor charge pump system (Cockroft-Walton circuit) which is fully immersed in the liquid

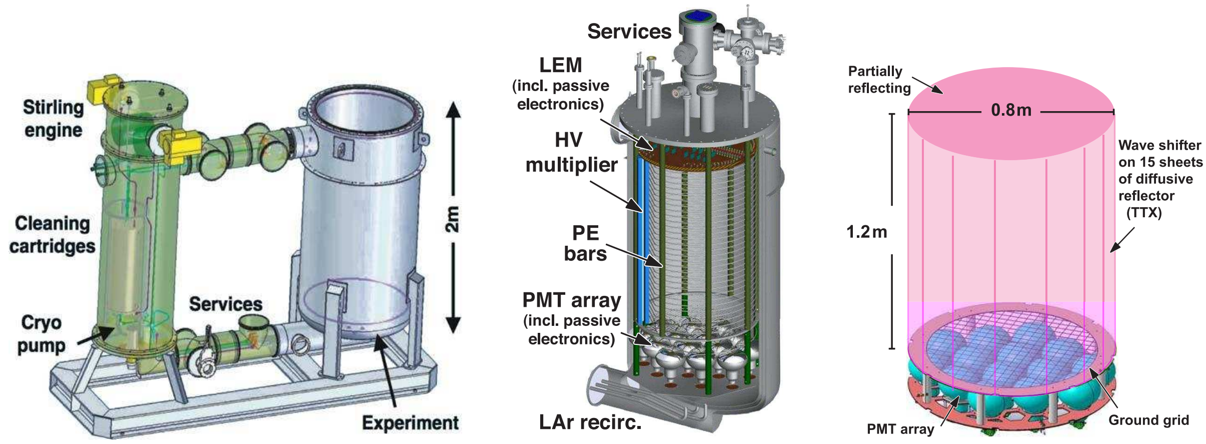

Figure 3. Left: cryo-system and main dewar; middle: detector components mounted to the top flange by polyethylene bars; right: arrangement of the wavelength-shifter/reflector foils in light diffusion cell arrangement inside the field shaper rings.

argon and designed to reach up to -500 kV (≈ 4 kV/cm) at the bottom cathode. Another unique feature of the experiment is the use of a LEM, which is placed 5 mm above the liquid level in the gas. The positional readout is achieved by segmenting the upper LEM surface and the anode plate with 1.5 mm wide x and y-strips respectively. In total there are 1024 readout channels which are AC coupled to charge sensitive preamplifiers located externally on the top flange of the apparatus. Because the LEM is operated in very pure argon gas, which cannot quench charge avalanches, it has to be built with considerable attention to HV discharges. To read scintillation light homogeneously over the full volume we adopted a (wave shifting) diffusion cell design with the PMT array at the bottom in the liquid. This keeps the system simple [4] and scalable. The shifting of the VUV into the range of high quantum efficiency of the bialkali PMTs is done by a thin layer ($\approx$1 mg/cm^2) of tetraphenylbutadiene (TPB) evaporated onto 15, cylindrically arranged, 25 cm wide reflector sheets which are located in the vertical electric field. These sheets, made out of the PTFE fabric Tetratex$^{\mathrm{TM}}$ (TTX), are clamped to the upper- and lowermost field shaper rings. The PMTs (Hamamatsu R5912-02MOD-LRI) were made from particularly radiopure borosilicate glass and are sensitive to single photons. They are equipped with with a Pt-underlay under their photocathodes for operation at LAr temperatures. This ineluctably reduces their quantum efficiency by roughly one third to a value between 15 and 20% [15]. The PMT glass windows are also coated with TPB to convert directly impinging VUV photons. The average number of recorded photoelectrons (n_{pe}) is expected (laboratory measurements) to be in the order of 1 pe/keV$_{ee}$. The development of the light detection system and particularly

[4] large area VUV sensitive photosensors, e.g. MgF_2 windowed PMTs are commercially not available

the operation of gaseous argon test cells with α particle excitation were described in earlier work [16, 17, 18].

4. First test run of ArDM on the full 1 ton LAr target

A first run of the experiment was undertaken in May 2009 to test cryogenic functionality (incl. various safety installations) with a prototype light read out system (7 PMTs out of 14 were mounted). No internal electric field was yet present but background events and more over the response of the detector to external gamma sources could be explored for the first time. Cryogenics proofed to work well, showing stable operation at high argon purity over the full 2 weeks of operation despite no liquid recirculation and cleaning. LAr purity was monitored by the lifetime of the second scintillation component (see [17] for details on this technique), recording a stable high value of ≈ 1500 ns over the entire test period. Figure 4 shows the response of the detector to external gamma sources ^{137}Cs (190 kBq) and ^{22}Na (20 kBq), where the emission of the latter was controlled and triggered by an external crystal scintillator. The shoulders of full gamma absorption are marked with arrows. Dashed spectra stem from data triggered on large PMT signals at a threshold of roughly 150 keV$_{ee}$ (^{22}Na data was taken in coincidence with the crystal). The full, grey spectrum was recorded triggering on the external crystal only and shows an unbiased 511 keV response (event reconstruction down to 50 keV$_{ee}$ possible). We find an average yield for the prototype light read out of ≈ 0.5 pe/ keV$_{ee}$, well in agreement with the expected number of around 1 pe/ keV$_{ee}$ of a fully equipped detector. A first comparison of the spectra with MC confirms an average value of 18% for the light yield of the Pt-underlay PMTs.

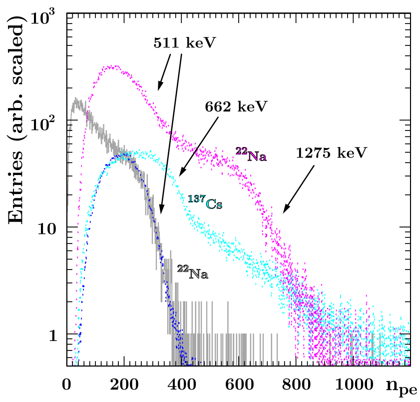

Figure 4. gamma spectra in ArDM.

While R&D work for sub detector parts is now finalising, main mechanical components are set together at CERN. Following a successful commissioning at surface we consider a deep underground operation.

Acknowledgments

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